

Very high energy emission of Crab-like pulsars driven by the Cherenkov drift radiation.

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ABSTRACT

In this paper we study the generation of very high energy (VHE) emission in Crab-like pulsars driven by means of the feedback of Cherenkov drift waves on distribution of magnetospheric electrons. We have found that the unstable Cherenkov drift modes lead to the quasi-linear diffusion (QLD), keeping the pitch angles from vanishing, which in turn, maintains the synchrotron mechanism. Considering the Crab-like pulsars it has been shown that the growth rate of the Cherenkov drift instability (ChDI) is quite high, indicating high efficiency of the process. Analyzing the mechanism for the typical parameters we have found that the Cherenkov drift emission from the extreme UV to hard X -rays is strongly correlated with the VHE synchrotron emission in the GeV band.

Key words: Pulsars: general - instabilities: physical data and processes - radiation mechanisms: non-thermal

1 INTRODUCTION

Last decade results from the new facilities: Very Energetic Radiation Imaging Telescope Array System (VERITAS) and Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) Telescope have significantly stimulated an interest to VHE gamma ray observations.

In particular, the VERITAS collaboration has reported the pulsed gamma ray emission from the Crab pulsar above 100 GeV (Aliu et al. 2011), which later have been confirmed by the MAGIC observations (Aleksić et al. 2011, 2012). It is obvious that such energetic photons are emitted by VHE particles. On the other hand, the pulsar magnetosphere is mainly composed of electron-positron pairs which, by means of the centrifugal mechanism of acceleration might achieve extremely high energies in the light cylinder area (a hypothetical zone, where the linear velocity of rotation exactly equals the speed of light) (Osmanov Z. & Rieger 2009; Mahajan et al. 2013; Osmanov et al. 2015). Usually, the major question which arises in the context of these observations is to understand and identify concrete mechanisms responsible for generation of VHE photons.

In general, it is strongly believed that VHE gamma-rays are produced either by the inverse Compton or by the curvature radiation mechanism. In particular, on the light cylinder surface in the magnetospheres of the Crab-like pulsars the magnetic field is of the order of $B \sim 10^6$ G,

which efficiently suppresses the synchrotron mechanism of radiation. Indeed, the cooling timescale for this process is given by $t_{syn} \sim \gamma mc^2 / P_{syn}$, where γ is the Lorentz factor of an electron, m is the electron's mass, c is the speed of light, $P_{syn} \approx 2e^4 \gamma^2 B^2 \sin^2 \psi / 3m^2 c^3$ is the electron's synchrotron emission power, e is the electron's charge and ψ is the pitch angle. The above expression for t_{syn} applied to the relativistic electrons with $\gamma \sim 10^7$ (Osmanov Z. & Rieger 2009) for $\sin \psi \sim 1$ leads to the cooling timescale of the order of 10^{-10} s, which is by many orders of magnitude less than the kinematic timescale, or the escape timescale $t_{kin} \sim R_{lc}/c \sim P_{Cr}/2\pi$, where R_{lc} is the light cylinder radius and $P_{Cr} \sim 0.033$ s is the Crab pulsar's rotation period. This means that particles very rapidly transit to the ground Landau states and as a result the emission process should damp.

In a series of papers (Machabeli & Osmanov 2009, 2010; Osmanov 2011; Chkheidze et al. 2011; Chkheidze & Osmanov 2012; Chkheidze et al. 2013) the authors have shown that the pulsar magnetospheres might provide necessary conditions for keeping the pitch angles from damping, thus, maintaining the synchrotron mechanism. The major process responsible for keeping the synchrotron emission from damping is the QLD. In particular, Kazbegi et al. (1991) have shown that plasmas with strong magnetic field may generate very unstable cyclotron waves, which in turn, via the QLD influence the particle distribution across the magnetic field lines (Lominadze et al. 1979). This process inevitably leads

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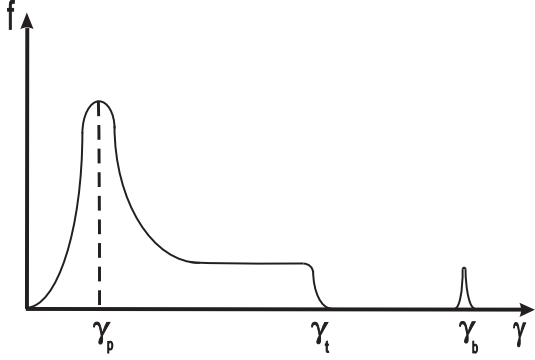


Figure 1. Magnetospheric electrons' distribution function versus the Lorentz factor. The function consists of two major sections: the first - wider area corresponds to the so-called plasma component and the relatively narrower region corresponds to the primary Goldreich-Julian beam particles.

to the creation/maintaining of the pitch angles making the synchrotron radiation a working mechanism despite the efficient energy losses. Another interesting feature of this mechanism is that the QLD provides emission in two different frequency bands: one generated by the cyclotron modes and another produced directly by the synchrotron radiation.

In general, distribution of particles might be influenced not only by the cyclotron waves but also by the Cherenkov-drift waves, finally driving the synchrotron process. In particular, in our recent work (Osmanov & Chkheidze 2013) we have considered the synchrotron emission, generated by means of the feedback of Cherenkov drift waves on the particle distribution in the active galactic nuclei. It has been argued that in the light cylinder area the Cherenkov drift instability is strong enough to prevent the pitch angles from damping, keeping the synchrotron mechanism active and providing strongly correlated emission in different energy bands.

In the present paper we consider the Crab-like pulsars and study the synchrotron process maintained by means of the QLD driven by the Cherenkov drift instability.

The paper is arranged in the following way. In section II, we introduce the theory of the Cherenkov driven synchrotron emission. In section III, we apply the model to Crab-like millisecond pulsars and obtain results and in section IV, we summarize them.

2 EMISSION MODEL

In this section we consider the light cylinder area of magnetospheres of the Crab-like pulsars and develop the model of synchrotron emission maintained by means of the feedback of the Cherenkov drift instability. It is strongly believed that in the mentioned zone by means of a direct centrifugal mechanism of acceleration electrons might achieve Lorentz factors of the order of 10^7 (Osmanov Z. & Rieger 2009). In the framework of the paper we suppose that the magnetospheric particles are distributed according to the Fig. 1. The distribution function is composed of two major parts. The narrower "region" represents the primary beam components and the wider "area" is a result of the pair cascading

processes, which is considered in detail by Sturrock (1971); Tadamaru (1973). By γ_b we indicate the Lorentz factor of the beam component, γ_t is the Lorentz factor of the tail and γ_p represents the Lorentz factor in the wider "section" of the plot.

Particles moving in a medium with curved magnetic field lines experience drift across the plane of the curvature and the corresponding velocity is given by

$$u_x = \frac{\gamma_b c^2}{\omega_B \rho}, \quad (1)$$

where $\omega_B = eB/(mc)$ represents the cyclotron frequency and ρ is the curvature radius of the field line. From the above equation it is clear that for ultra relativistic electrons the drift velocity might become relativistic as well and as is shown by Shapakhidze et al. (2002), under these circumstances the ChDI arises with the following resonance condition

$$\omega - k_{\parallel} v_{\parallel} - k_x u_x = 0, \quad (2)$$

where by k_{\parallel} and v_{\parallel} we denote the wave vector's and velocity's longitudinal (along the magnetic field line) components respectively and k_x is the wave vector's component along the drift. According to the theory developed by Shapakhidze et al. (2002) the plasma component with the Lorentz factor γ_p and the beam component with γ_b lead to the unstable Cherenkov drift waves with the increment given by

$$\Gamma = \frac{\pi}{2} \frac{\omega_b^2}{\omega} \frac{\gamma_b}{\gamma_p^2}, \quad (3)$$

where by

$$\omega = \frac{\omega_b \gamma_b c}{\gamma_p^{3/2} u_x} \quad (4)$$

we denote the frequency of Cherenkov emission, $\omega_b = \sqrt{4\pi n_b e^2/m}$ is the plasma frequency of the beam component and n_b is the corresponding number density (Osmanov & Chkheidze 2013).

For considering the QLD one has to note that it is governed by two forces. One is the synchrotron radiation reaction force with the following components

$$F_{\perp} \approx -\alpha \frac{p_{\perp}^3}{p_{\parallel} m^2 c^2}, \quad F_{\parallel} \approx -\frac{\alpha}{m^2 c^2} p_{\perp}^2, \quad (5)$$

where p_{\perp} and p_{\parallel} are transversal and longitudinal components of momentum respectively and $\alpha = 2e^2 \omega_B^2 / 3c^2$. On the other hand, the relativistic particles moving in a non uniform magnetic field experience another force responsible for the conservation of the adiabatic invariant $I = 3cp_{\perp}^2/2eB$. The corresponding components of this force are given by (Landau & Lifshitz 1971)

$$H_{\perp} = -\frac{c}{\rho} p_{\perp}, \quad H_{\parallel} = \frac{c}{\rho p_{\parallel}} p_{\perp}^2. \quad (6)$$

It can be shown that for relatively small pitch angles when the following condition $\partial/\partial p_{\perp} \gg \partial/\partial p_{\parallel}$ is satisfied, the kinetic equation governing the QLD writes as (Machabeli & Usov 1979; Malov & Machabeli 2001; Osmanov & Chkheidze 2013)

$$\frac{\partial f^0}{\partial t} + \frac{1}{p_{\perp}} \frac{\partial}{\partial p_{\perp}} (p_{\perp} [F_{\perp} + H_{\perp}] f^0) = \frac{1}{p_{\perp}} \frac{\partial}{\partial p_{\perp}} \left(p_{\perp} D_{\perp, \perp} \frac{\partial f^0}{\partial p_{\perp}} \right). \quad (7)$$

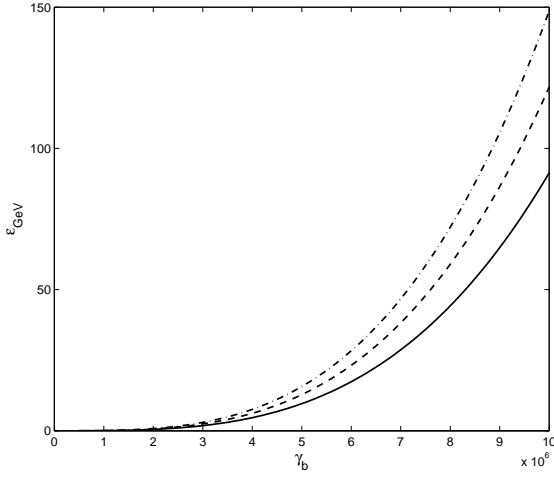


Figure 2. Dependence of energy of synchrotron photons on the Lorentz factors of the beam electrons for different values of plasma component's Lorentz factors: $\gamma_p = 1$ (solid line), $\gamma_p = 10$ (dashed line), $\gamma_p = 50$ (dashed-dotted line). The set of the parameters is: $P = P_{Cr}$, $\dot{P} = \dot{P}_{Cr}$, $n_b = n_{GJ}$, $R = 10^6$ cm. γ_b varies in the interval $[0.5; 1] \times 10^7$.

where by $f^0(\mathbf{p})$ we denote the distribution function of electrons,

$$D_{\perp,\perp} = 8\pi \left(\frac{u_x}{c}\right)^8 \left(\frac{e}{mc}\right)^2 \frac{W}{\Gamma_k} \quad (8)$$

is the transversal coefficient of diffusion and $W = \gamma_b n_b m c^2$ (Osmanov & Chkheidze 2013).

By combining Eqs. (5,6) and by taking into account that the pitch angle ψ is given by p_{\perp}/p_{\parallel} one can derive for the typical parameters of Crab-like pulsars the following relation between the corresponding components of the forces

$$\begin{aligned} \frac{H_{\perp}}{F_{\perp}} &\approx 1.1 \times 10^{-4} \times \frac{P_{Cr}}{P} \times \frac{\dot{P}_{Cr}}{\dot{P}} \times \\ &\times \frac{R_{lc}}{\rho} \times \frac{10^7}{\gamma_b} \times \left(\frac{0.01 \text{ rad}}{\psi}\right)^2, \end{aligned} \quad (9)$$

where P is the pulsar's rotation period, $\dot{P} \equiv |dP/dt|$ is the modulus of its time derivative, $\dot{P}_{Cr} \approx 4.21 \times 10^{-13} \text{ ss}^{-1}$ is the corresponding value for the Crab pulsar and we have taken into account that the magnetic field has a dipolar behavior and close to the pulsar's surface its induction is given by $B \approx 3.2 \times 10^{19} \times \sqrt{P\dot{P}} \text{ G}$ (Goldreich & Julian 1969). From the above estimation it is clear that H_{\perp} can be neglected for the realistic physical parameters. Therefore Eq. (9) for the stationary regime ($\partial/\partial t = 0$) reduces to the equation

$$\frac{\partial}{\partial p_{\perp}} (p_{\perp} F_{\perp} f^0) = \frac{\partial}{\partial p_{\perp}} \left(p_{\perp} D_{\perp,\perp} \frac{\partial f^0}{\partial p_{\perp}} \right), \quad (10)$$

with the following solution (Osmanov & Chkheidze 2013)

$$f(p_{\perp}) = C e^{-\left(\frac{p_{\perp}}{p_{\perp 0}}\right)^4}, \quad (11)$$

where

$$p_{\perp 0} = \left(\frac{4\gamma_b m^3 c^3 D_{\perp,\perp}}{\alpha} \right)^{1/4}. \quad (12)$$

Since the particles are distributed with the transverse momentum, it is worthwhile to define the average value of the pitch angles

$$\langle \psi \rangle = \frac{1}{p_{\parallel}} \frac{\int_0^{\infty} p_{\perp} f(p_{\perp}) dp_{\perp}}{\int_0^{\infty} f(p_{\perp}) dp_{\perp}} = \frac{\sqrt{\pi}}{4\Gamma(\frac{5}{4})} \frac{p_{\perp 0}}{p_{\parallel}}, \quad (13)$$

leading to the following energy of synchrotron photons (Rybicki & Lightman 1979)

$$\epsilon_{GeV} \approx 3 \times 10^{-18} \gamma_b^2 B_{lc} \frac{\sqrt{\pi}}{\Gamma(\frac{5}{4})} \frac{p_{\perp 0}}{p_{\parallel}}. \quad (14)$$

where $\Gamma(x)$ is the gamma function.

3 MAIN RESULTS

In this section we apply the theoretical model to the Crab-like pulsars. Since the QLD is a result of the ChDI, it is important to know how efficient is the corresponding process. By considering the so-called beam and plasma components, one obtains from Eq. (3)

$$\Gamma \approx 1.4 \times 10^4 \times \gamma_p^{-1/2} \times \frac{\gamma_b}{10^7} \times \frac{R_{lc}}{\rho} \times \left(\frac{P_{Cr}}{P}\right)^{3/4} \times \left(\frac{\dot{P}_{Cr}}{\dot{P}}\right)^{1/4} \quad (15)$$

It is clear that for the typical parameters of the Crab-like pulsars the instability timescale $t_{ins} \sim 1/\Gamma \sim 10^{-4} \text{ s}$, which is much less than the kinematic timescale, which indicates the high efficiency of the ChDI, generating the relatively low energy photons with energies (see Eq. (4))

$$\epsilon_{keV}^{Ch} \approx 4.7 \times \gamma_p^{-3/2} \times \frac{\rho}{R_{lc}} \times \left(\frac{P}{P_{Cr}}\right)^{1/4} \times \left(\frac{\dot{P}}{\dot{P}_{Cr}}\right)^{3/4}. \quad (16)$$

As we see, in the magnetospheres of Crab-like pulsars the Cherenkov drift resonance might lead to the hard X-rays. In the previous section we have seen that this emission inevitably leads to the non vanishing pitch angles (see Eq. (14)), generating the synchrotron emission. In Fig. 2 we show the behavior of energy of synchrotron photons, ϵ_{GeV} versus γ_b in the interval $[0.5; 1] \times 10^7$ for different values of Lorentz factors of the plasma component: $\gamma_p = 1$ (solid line), $\gamma_p = 10$ (dashed line), $\gamma_p = 50$ (dashed-dotted line). We have taken into account the dipolar character of the magnetic field, $B \approx 3.2 \times 10^{19} \times \sqrt{P\dot{P}} \times R^3/R_{lc}^3 \text{ G}$ (Goldreich & Julian 1969), where $R = 10^6 \text{ cm}$ is the neutron star's radius. The rest of the parameters is: $P = P_{Cr}$, $\dot{P} = \dot{P}_{Cr}$, $n_b = n_{GJ}$, where $n_{GJ} = B/Pec$ is the Goldreich-Julian number density (Goldreich & Julian 1969). As it is evident from the plots by increasing γ_p , the resulting emission energy increases as well, which directly follows from the analytical behaviour, $\epsilon_{GeV} \propto \gamma_p^{1/8}$ (this can be seen by combining Eqs. (8,12-14)). We see that the QLD by means of the feedback of ChDI guarantees the synchrotron emission over 100 GeV. We can roughly estimate the possible VHE luminosity by multiplying the number of particles involved in the process with the single emission power, $P_{syn} \approx 2e^4 \gamma_b^2 B^2 \langle \psi \rangle^2 / 3m^2 c^3$. It is worth noting that the thickness of the layer, d , where the electrons accelerate to the highest energies, is of the

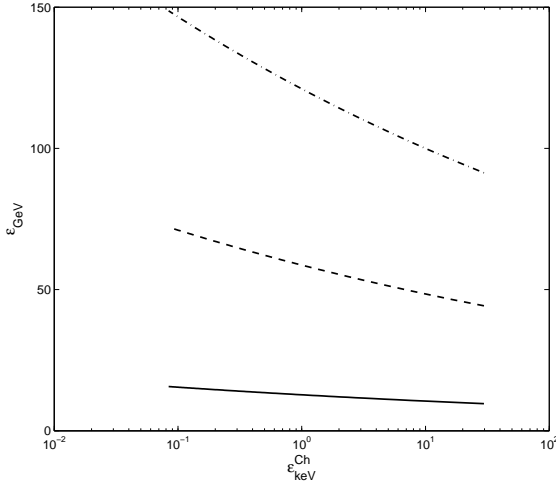


Figure 3. Behaviour of $\epsilon_{GeV}(\epsilon_{keV}^{Ch})$ for different values of the Lorentz factors of the beam component: $\gamma_b = 5 \times 10^6$ (solid line), $\gamma_b = 8 \times 10^6$ (dashed line), $\gamma_b = 10^7$ (dashed-dotted line). The set of the parameters is: $P = P_{Cr}$, $\dot{P} = \dot{P}_{Cr}$, $n_b = n_{GJ}$, $R = 10^6$ cm. γ_p varies in the interval $[1; 50]$.

order of $R_{lc}/2\gamma_b$. Then, by taking into account the corresponding number of particles, $4\pi R_{lc}^2 n_{GJ} d$, one can show that in the emission energy band 150 GeV the highest energy electrons lead to the bulk luminosity of the order of 10^{33} erg s $^{-1}$ which is in a good agreement with observations (Lessard et al. 2000; Albert et al. 2008).

An interesting feature of this mechanism is that the VHE radiation is strongly linked to the lower energy emission provided by the ChDI. In Fig. 3 we show plots for $\epsilon_{GeV}(\epsilon_{keV}^{Ch})$ for three values of the beam Lorentz factors $\gamma_b = 5 \times 10^6$ (solid line), $\gamma_b = 8 \times 10^6$ (dashed line), $\gamma_b = 10^7$ (dashed-dotted line). The set of the parameters is: $P = P_{Cr}$, $\dot{P} = \dot{P}_{Cr}$, $n_b = n_{GJ}$, $R = 10^6$ cm and the plasma component lorentz factor varies in the interval $[1; 50]$. We see that for the mentioned physical parameters the Cherenkov drift photons have energies in the interval $\sim [0.02; 30]$ keV, which are strongly correlated with the VHE emission in the energy band $[20; 150]$ GeV.

It is interesting to study the generation of VHE synchrotron emission for a variety of Crab-like pulsars. For this purpose in Fig. 4 we show the dependence of energy of synchrotron photons on pulsar's period for different values of γ_p : $\gamma_p = 1$ (solid line), $\gamma_p = 10$ (dashed line), $\gamma_p = 50$ (dashed-dotted line). The set of the parameters is: $P = [0.01; 0.05]$ s, $\gamma_b = 10^7$, $\dot{P} = \dot{P}_{Cr}$, $n_b = n_{GJ}$, $R = 10^6$ cm. From the figure it is clear that depending on the period, for the above parameters, the synchrotron emission might provide energies up to ~ 200 GeV.

The investigation shows that the Crab-like pulsars might provide VHE synchrotron radiation strongly connected with the Cherenkov drift emission.

4 SUMMARY

The main aspects of the present work can be summarized as follows:

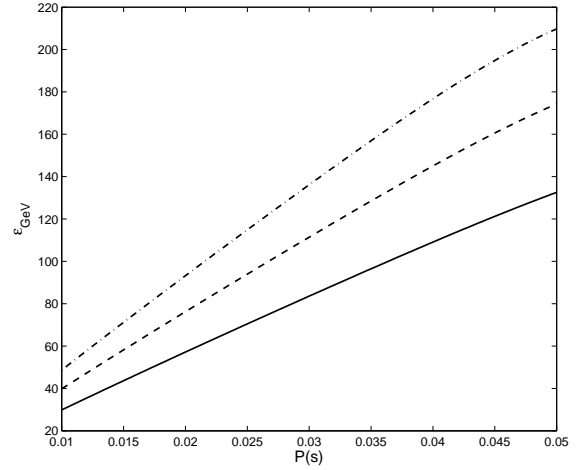


Figure 4. Dependence of ϵ_{GeV} versus P for three different values of γ_p : $\gamma_p = 1$ (solid line), $\gamma_p = 10$ (dashed line), $\gamma_p = 50$ (dashed-dotted line). The set of the parameters is: $P = [0.01; 0.05]$ s, $\gamma_b = 10^7$, $\dot{P} = \dot{P}_{Cr}$, $n_b = n_{GJ}$, $R = 10^6$ cm.

(i) We have studied the VHE synchrotron emission process driven by the feedback of the ChDI on the distribution function of electrons in the Crab-like pulsars.

(ii) Considering the two component magnetospheric plasmas, we have developed the analytical model for studying the QLD. For this purpose the kinetic equation governing the mentioned process has been applied and analysed for the light cylinder zone. It has been found that under certain conditions the ChDI is very efficient, resulting in the creation of the pitch angles, which in turn prevents the synchrotron mechanism from damping despite the strong magnetic field.

(iii) Analyzing the radiation mechanism versus several physical parameters, we have shown that the Crab-like pulsars might provide synchrotron photons with 100s of GeV strongly correlated with the Cherenkov drift emission from the extreme UV (20 eV) to the hard X-rays (30 keV).

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REFERENCES

- Albert J., Aliu, E., Anderhub, H., et al., 2008, ApJ, 674, 1037
- Aleksić, J., Alvarez, E. A., Antonelli, L. A., et al. 2011, ApJ, 744, 43
- Aleksić, J., Alvarez, E. A., Antonelli, L. A., et al. 2012, A&A, 540, 69
- Aliu, E., Arlen, T., Aune, T., et al. 2011, Sci, 334, 69
- Chkheidze, N., Machabeli, G. & Osmanov, Z., 2013, ApJ, 773, 7
- Chkheidze, N., Machabeli, G. & Osmanov, Z., 2011, ApJ, 730, 62
- Chkheidze, N. & Osmanov, Z., 2012, MNRAS, 419, 239

- Goldreich, P. & Julian, W. H., 1969, *ApJ*, 157, 869
- Kazbegi, A. Z., Machabeli, G. Z., & Melikidze, G. I. 1991, *MNRAS*, 253, 377
- Landau, L. D., & Lifshitz, E. M. 1971, *Classical Theory of Fields* (London: Pergamon)
- Lessard, R. W., Bond, I. H., Bradbury, S. M., et al., 2000, *ApJ*, 531, 942
- Lominadze J.G., Machabeli G.Z. & Mikhailovsky A.B., 1979, *J. Phys. Colloq.*, 40, No. C-7, 713
- Machabeli, G. & Osmanov Z., 2010, *ApJ*, 709, 547
- Machabeli, G. & Osmanov Z., 2009, *ApJL*, 700, 114
- Machabeli G.Z. & Usov V.V., 1979, *AZh Pis'ma*, 5, 445
- Mahajan, S., Machabeli, G., Osmanov, Z. & Chkheidze, N., 2013, *Nat. Sci. Rep.* 3, 1262
- Malov I.F. & Machabeli G.Z., 2001, *ApJ*, 554, 587
- Osmanov Z., 2011, *MNRAS*, 411, 973
- Osmanov Z. & Chkheidze, N., 2013, *ApJ*, 764, 59
- Osmanov, Z., Mahajan, S., Machabeli, G. & Chkheidze, N., 2015, *Nat. Sci. Rep.*, 5, 14443
- Osmanov Z. & Rieger F., 2009, *A&A*, 502, 15
- Rybicki, G.B. & Lightman, A. P., 1979, *Radiative Processes in Astrophysics*. Wiley, New York
- Shapakidze, D., Machabeli, G., Melikidze, G. & Khechinashvili, D., 2003, *Phys. Rev. E*, 2, 026407
- Shapakidze, D., Melikidze, G. & Machabeli, G., 2002, *A&A*, 394, 729
- Sturrock, P. A., 1971, *ApJ*, 164, 529
- Tadamaru, E., 1973, *ApJ*, 183, 625

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